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SHIP ARRANGEMENTS AND COMBAT SYSTEM PERFORMANCE

by

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Arrangements, which involve the geometrical features of warship design, have two aspects. One aspect is the geometrical relationship between components; the other aspect includes the quantitative geometrical variables of length, area, volume, shape, and location. About one-half of the paper is devoted to background information concerning interaction between arrangements and various ship characteristics. Topics discussed include items such as seakeeping, sensor location, topside design, weapon location,

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habitability, and NBC protection. Several different models can be developed to assess arrangements. One approach is to introduce the quantitative aspect of arrangements (length, volume, etc.) into the overall ship design process. The relationship aspect of arrangements is an input made by the designer. Once the design of a warship has converged and has been optimized, the ship can be subjected to combat simulation. During the combat simulation, the relationship aspect can be assessed. Two optimized warships differing in relationship of components fight the same battle. Based on performance in the combat simulation, one ship will be superior.

An approach based on subsystems and the interaction between subsystems has been formulated. The formulation is a useful tool for identification of interactions; however, the subsystem method seems less dir :t than the two step process of overall ship design and combat simulation.

Two appendices are included. One appendix outlines an analytical model which highlights interaction between a dipole antenna and the metal walls of the superstructure. The second appendix discusses use of a linear matrix approach for subsystem arrangement. The approach fails because many interactions are nonlinear.

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SHIP ARRANGEMENTS AND COMBAT SYSTEM PERFORMANCE

by

A. E. Fuhs*

I. INTRODUCTION

The process of synthesizing a warship is known as design; arrangements are a subset of design. Arrangements deal with geometry, i.e., area, volume location, length, and shape. Arrangements involve the geometrical relationship between components or subsystems.

In aircraft and missile design, "configuration" is synonymous with "arrangements" in naval architecture and marine engineering. See, for example, Dow [1], Chin [2], Puckett and Ramo [3], and Corning [4]. Many of the features of missile or aircraft configuration selection have analogous counterparts in arrangements selection. One example is the relation between center of gravity and vehicle stability.

Looking at some of the standard reference texts for the naval architect and marine engineer is interesting although not too enlightening. Ship Design and Construction [5] has one chapter entitled "General Arrangement." Neither Principles of Naval Architecture [6] nor Marine Engineering [7] mentions arrangements.

Arrangement is one of the basic decisions involved with warship design. The allocation of deck space and volume within the hull and superstructure is an important function. A figure-of-merit is needed to assess the merit of alternative arrangements. The figure-of-merit would be of value in conceptual design when many different arrangements are screened. Currently assessment of arrangements is a judgmental factor which rests on the opinion

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of the naval architect and marine engineer. A figure-of-merit for arrangements would make the process quantitative.

A related question to the figure-of-merit is the engineering basis for a quantitative measure of "arrangements." Are there fundamental theorems from topology, differential geometry, or other science which establish a figure-of-merit? The answer is negative; any figure-of-merit is an arbitrarily defined quantity. Nonetheless useful figures-of-merit can be defined.

Complex definitions based on extensive models can be used for the figure-of-merit. The speed of the computer allows us of extensive numerical models which incorporate the various ramifications of a particular arrangement.

Certain aspects of arrangements are well defined and are mathematically precise. One aspect is ship stability. Arrangements determine the height of the center of gravity above the keel, KG. Stability considerations impose an upper bound for KG. Arrangements determine the moment of inertia about the roll axis. Considerations of ride quality and stabilization of antennas impose limits on roll rates which are acceptable.

Other aspects of arrangements are less well defined. An example is the location of CIC. For convenience to the ship's CO, the CIC should be near the bridge. From vulnerability considerations, CIC should be buried deep within the hull. Based on these two considerations--convenience versus vulnerability--arrangements which specify location of CIC are matters of judgment. The judgment could be made quantitative by suitable weighting values.

Section II of this paper discusses various topics related to arrangements. Section III outlines several models for an arrangements figure-of-merit. Section IV describes one model, which is a Monte Carlo simulation of an engagement.

II. BACKGROUND DISCUSSION OF ARRANGEMENTS

As a point of departure in the quest for a rational and useful figure-of-merit for arrangements, numerous topics involving ship design and performance are discussed relative to arrangements.

SHIP HULL AND STRUCTURE

The ship hull shape determines numerous ship characteristics and properties such as ship resistance, self generated flow noise, seakeeping ability, metacentric height, stability, and maneuvering capability. Further, the ship hull shape and structural philosophy determine the internal volume available for allocation to numerous components and subsystems. For reasons of hydrodynamics, the hull is not a rectangular box. A box is a shape which is convenient for packaging. The hull complex curvature imposes contraints on space utilization.

Ship Stability

As mentioned earlier, arrangements determine the location of the center of gravity vertically as well as fore and aft and moments of inertia about the roll and pitch axes. For damaged stability, the hull is subdivided to limit flooding. Arrangements have a large impact on allowable subdivision of the hull.

The location of center of gravity has an influence on righting arm, RA, through the equation

$$RA = (KM - KG) \sin \theta \tag{1}$$

where KM is metacentric height about the keel, KG is height of center of gravity above the keel, and θ is the angle of heel. In addition, KG is one of the variables which determines the angle of heel in a high speed turn.

Arrangements determine the sail area of a ship. During high winds, the ship acquires an angle of heel as a result of the force of the wind.

During ship design, intact and damaged stability are assessed using criteria discussed by Sarchin and Goldberg [8]. A well understood interaction between stability and arrangements exists.

Seakeeping

Seakeeping involves the random dynamic motion of a ship in response to a random sea condition. Such responses as slamming, shuddering, green water over the deck, deck wetness, and maximum speed are part of seakeeping.

Kehoe [9] discusses the relative seakeeping characteristics of the United States Navy and Soviet ships. Olson [10] provides an evaluation of seakeeping qualities.

How does arrangement influence seakeeping?

The random waves acting on a given hull shape provide the forces. The ship responds to the forces according to the distribution of mass. The distribution of mass is directly related to arrangements.

Further, the distribution of mass has an influence on the structural design and the distribution of strength. This fact leads one to hull flexure.

Hull Flexure

Due to wave action, a destroyer size hull has milliradian angular displacements. The angular displacement may be twist between bow and stern or may be due to hogging or sagging.

The hull flexure creates problems in the fire control system. A F/C sensor may be located at one position on the ship and measure a certain set of values for elevation and azimuth. Orders for a gun in train and elevation or for a missile launcher are computed on the basis of a rigid hull. Bending causes an error. The magnitude of the error increases with

increasing separation between components, e.g., F/C radar and the gun mount. The error is partially an arrangements factor.

Weiss and Cross [11] discuss the influence of both rigid ship motion and hull flexure on gun fire control systems.

SHIP CHARACTERISTICS

Several ship characteristics such as vulnerability, NBC protection, shock protection, and detectability will now be discussed in regard to arrangements.

Vulnerability/Survivability

Vulnerability is a ship characteristic related to the extent of damage which a ship receives as a result of exposure to a specified weapon under well defined conditions. If the weapon is a warhead, the location of the detonation must be specified. Survivability is the ship characteristic related to the retention of combat capability in spite of exposure to weapons. Vulnerability is the loss of capability, whereas survivability is the retention of capability.

As discussed by Jolliff [12], survivability can be enhanced through two general approaches. The first approach is passive hardening which involves armor, torpedo side protection, redundancy, reduced observables (radar cross section, IR signature) and low profile. The second approach involves active hardening associated with EW, decoys, and defensive weapons.

Arrangements play a major role in passive hardening. The profile of a ship is a direct consequence of an arrangement. A low profile implies a target which is difficult to hit. Ship observables such as radar cross section are influenced by arrangements. Large flat vertical sides yield

large cross section; however, radar cross section has subtleties. Hand railing may be in resonance with a particular radar frequency greatly increasing cross section. Corners and sharp discontinuities can cause a radar cross section considerably larger than the projected area. The corner reflector is one example.

A good arrangement gives low observables and a low profile. The low profile is easy to quantify; it is merely the projected area. To relate radar cross section to arrangements, more effort is required. One is forced to consider basic electromagnetic wave reflection and diffraction.

In some cases, missile guidance aims for the geometric centroid of a target. If the centroid is, in fact, the aimpoint, then the centroid is most likely to be hit. Arrangements which account for the aimpoint can enhance survivability.

Depending on the weapon, certain locations on a ship are less vulnerable. For example, a location near the keel is safe relative to an air burst of a fragmentation warhead. Hence location within the ship, which is certainly an arrangements factor, has an important effect on survivability.

Nuclear weapon effects add to the complexity of designing a survivable ship. Electromagnetic pulse, EMP, is an effect caused by an exoatmospheric burst. Electric fields occur at 2000 miles from the burst with sufficient magnitude to destroy sensitive solid state electronics. According to Carstensen [13], circuits which are internal to the hull or superstructure are shielded by the metal bulkheads. The extent of shielding depends on location; shielding for EMP is partially an arrangements factor.

NBC Protection

A case is made by Haupt [14] that nuclear warfare on high seas is unlikely, whereas either biological or chemical warfare is to be expected at sea. For protection, the German Navy uses the "citadel" concept. Within the citadel, the crew is protected from biological or chemical weapons. Parts of the ship, e.g. engine room and helicopter hangar, are not within the citadel.

Using a citadel for NBC protection has implications relative to arrangements. All compartments within the citadel should be adjacent. Space must be allocated for air locks and decontamination stations to permit transit across the citadel boundaries.

Shock Protection

Arrangements have an influence on shock hardening. Consider an underwater explosion which accelerates the ship's bottom and keel upward. The pulse is transmitted upward platform by platform and deck by deck. The further from the keel, the more the pulse is attenuated by the ship's structure.

A trade-off exists between location and the amount of added material (springs, dampers, restraining straps) required to achieve the specified level of shock protection. Arrangements have an impact on shock hardening.

The value of shock protection from the point of view of the fleet has been stated by Read [15] and Pusey [16].

Detectability

Naval warfare has changed considerably since the turn of the century. Brodie [17] discusses naval tactics and strategy as these evolved during World War II. Fioravanzo [18] considers naval tactics from the days of oared ships to the 1970's. Many technological advances have influenced

naval warfare including missiles, radar, nuclear power, atomic explosives, computers, satellites, and jet propulsion. During a battle, opposing fleets are widely separated.

One of the most profound changes has been in the ability to detect the enemy's warships. The range has increased from the visual horizon with lookouts to worldwide detection using sea surveillance satellites.

The complete electromagnetic spectrum from megahertz radars to blue-green lasers is used for detection. Surveillance platforms range from surface ships and aircraft to satellites. Data bases for target position are used; the position data base uses all available information on a target (your own ship in this case) location. By correlating the information, future positions can be calculated although the accuracy degrades in time without updating. A worldwide data base would not be possible without very large computers.

During World War II, the fast carrier task forces in the Pacific frequently hid in rain squalls. See Dull [19] for an account of the Pacific war as seen from the Japanese side. Tod , hiding a task force in a rain squall is outmoded due to the numerous techniques to detect the task force.

One function of the ship designer is to reduce ship observables. Radar cross section has been discussed briefly. For passive infrared, the technique is to decrease the temperature of exposed surfaces. The spectral emissivity of various surfaces can be exploited occasionally. The exhaust plume from the propulsion plant needs to be cooled. With use of various techniques, the IR signature can be reduced greatly; however, the ship remains a warm object in a cold sea.

Consider the exhaust stack of a ship. Consider also a sea skimming missile attacking the ship. If the missile uses passive IR homing, the ship can thwart the missile to a degree. The hot spots on the ship can be placed

as low as possible and shielded for horizontal line of sight. Some aspects of intake and exhaust ducting are discussed by Rains, et al. [20].

Detectability is intertwined with arrangements.

SENSORS

An array of sensors is essential to a combat system. The relation between sensors and arrangements will now be discussed.

Radar

Many different types of antennas compete for space topside. Radar includes air search, surface search, navigation, and fire control. In addition to radar antennas, a need exists for electronic warfare, aircraft navigation, IFF, ship-to-ship communication, satellite communication, and ship-to-shore communication antennas. As emphasized by Law [21], crowding of antennas is unavoidable.

Antennas are excluded from many topside areas such as helicopter landing zones, UNREP deck areas, missile launch zones, gun arc-of-fire zones, boat handling areas, and visual navigation zones. Topside design is a specialized part of arrangements which must provide for all the topside functions and equipment including antennas. The topside design or arrangement must consider height and shape of the superstructure, masts, and stacks.

The difficult frequencies for antennas are in the range 2 to 30 MHz. The wavelengths which are obtained from

$$\lambda = \frac{c}{\nu} \qquad (2)$$

are 150 m to 10 m. In equation (2), λ is wavelength, c is speed of electromagnetic wave, and ν is frequency. Fortunately, the difficult frequencies can be modeled using brass ship models; see Rockway and DuBrul [22].

As an arrangements problem, antennas are particularly difficult. Radio and microwave frequency currents are driven in the ship structure. These currents modify antenna patterns.

In addition to the problem of achieving adequate antenna performance, the various hazards and interferences must be considered. McEachen and Mills [23] discuss the shipboard electromagnetic competibility program.

Of considerable interest currently is over-the-horizon, OTH, targeting; refer to Rimer [24]. Due to anomalous propagation, radar ducts may exist next to the ocean surface. Height of the antenna above the water has an influence on propagation within the duct. Antenna location is an arrangements problem.

Another approach to OTH targeting is to use remotely piloted vehicles, RPV. Space must be given for RPV operations. Deck area for RPV launch and recovery is an arrangements problem.

Mentioned earlier in connection with hull flexure was ship motion. Motion of antennas must be accounted for in the fire control solution according to Weiss and Cross [11]. Ship motion depends on arrangements.

Since many antennas are positioned on masts, blockage may occur. Mangulis [25] considers the issue of blockage for fire control antennas. Blockage is a geometrical factor and hence is a matter of arrangements.

<u>Electro-optical Sensors</u>

As discussed by Orelup [26], optics always have been used in naval warfare. The warships of World War II had range finders which used optics. Optics declined in importance with the advent of radar. Currently optics is experiencing a resurgence in interest due to the ance of associated

electronics. Imaging infrared sensors, low light level TV, high resolution TV, laser range finders, laser target designators, and laser illuminators are some of the new electro-optics, EO, developments with important military applications.

The location of an EO sensor has an important influence on performance. Fortunately most EO sensors are light weight and small in size. As an example of the importance of location to good performance, consider an IR sensor. Background radiation due to clouds, reflected sunlight from sea surface, and ship's stacks increases noise. An infrared sensor should be located remotely from the exhaust stack and the exhaust plume.

<u>Electronic Warfare/Decoys</u>

Several navies of the world have developed chaff dispensers and infrared decoys. Beulier [27] describes the Dagaie system developed for the French Navy as well as for export. Wood [28] lists the components of the Seafan System developed for the British Navy as well as for export. The Seafan System uses a 15-barrelled rocket launcher. The launcher launches the Honeydew infrared decoy or the Seafan chaff dispenser rocket. Both rockets are 105 mm in diameter. The launcher occupies approximately 2 m^2 of deck area.

Part of topside design is the selection of the location for decoy launchers.

<u>Underwater Sensors</u>

The primary underwater sensor for surface ships is sonar. Non-acoustic techniques, such as magnetic anomaly detection, are rarely used. Sonar may use hull mounted transducers or may use a towed array.

In the case of hull mounted transducers, noise generated by the ship hull and propulsion is important. Further the hydrodynamic shape of the

sonar dome is important. Noise due to flow over the dome can be generated by separated flow regions, turbulent boundary or shear layers, and cavitation. To lessen propeller noise, the dome can be located at the bow.

For towed arrays, deck space must be designated for deployment and recovery of the array. Towed arrays become another competitor for deck area.

EMI/RADHAZ/HERO/RFI

A host of hazards exist relative to electromagnetic equipment and antennas. Table I is a summary of electromagnetic terms which describe the various actions and effects. Table I is based on Read [15], Oller [29], Gartley [30], Duffy, Cain, and Cown [31], and Hoisington [32].

Serious problems involving electromagnetic effects exist in the fleet; Oller [29] reports one survey that resulted in eleven volumes listing 600 problems. As an example, according to Oller, it was standard practice to shut down certain search radars and communications transmitters when missile alert conditions were set in the Gulf of Tonkin.

The question arises as to what extent arrangements influence the various electromagnetic effects. At first glance, one would be tempted to state that there is negligible influence. However, Gartley [30] points out that for a communications antenna, and presumably more generally for all antennas, the radiation pattern, feedpoint impedance, and intercoupling of antennas depend on location of the antenna and the surrounding structure. Three words have been underlined to emphasize the relation between arrangements and the performance of electronic equipment.

Table II indicates the relation between arrangements and electromagnetic effects. Table II is not complete.

Table I. List of Electromagnetic Terms

ACRONYM	TERM	DEFINITION
EMC	ElectroMagnetic Compatibility	The ability of electronic equipment, or systems, to operate in a fixed environment within design levels of performance without degradation due to electromagnetic interference.
EMI	ElectroMagnetic Interference	Adverse interaction between electrical or electronic equipment.
EMV	ElectroMagnetic Vulnerability	Loss of performance of electronic equipment due to installation in adverse environment, interaction with other equipment, or enemy action.
EMP	ElectroMagnetic Pulse	Transient large electric field usually caused by exo-atmospheric nuclear explosion; damages solid state electronics.
ECM	Electromagnetic Counter Measures	Actions taken to prevent or reduce an enemy's effective use of electromagnetic spectrum.
ECCM	Electromagnetic Counter Counter Measures	Actions taken to insure friendly use of the electromagnetic spectrum despite ECM.
HERO	Hazards of Electromagnetic Radiation to Ordnance	Title is explicit; possible accidental detonation of ordnance as a result of electromagnetic radiation.
RADHAZ	RADiation HAZard	Hazard to personnel or equipment due to electromagnetic radiation.
EME	ElectroMagnetic Effect	An encompassing term which includes EMI, EMV, EMP, etc.
EW	Electronic Warfare	Intentional use of electromagnetic energy to deny hostile use of electromagnetic spectrum and to insure friendly use.

Table II. Relation of Arrangements to Electromagnetic Effects

ACRONYM	RELATION TO ARRANGEMENTS
EMC	Antenna and superstructure must be mutually designed so that electrical currents induced in superstructure do not add destructively to antenna currents and waves.
EMI	Interference may occur due to coupling between antennas; altered location of antennas may alter coupling. Interference may be due to electrical equipment. The diesel generator can generate interference along with power. Booms and cranes can distort severely antenna patterns.
EMP	Components susceptible to damage need shielding. The hull and superstructure, being metallic conductors, efficiently shield. Location determines shielding.
HERO	Near field antenna patterns must be small in regions where ordnance is handled.

To obtain a perspective on the interaction between antennas and metal walls, the solution of a dipole in a corner is discussed in Appendix A. The electromagnetic theory uses equations formulated by Stratton [33] and Wait [34].

The naval architect in charge of arrangements should NOT delve into the intracasies of electromagnetic wave theory and solutions to the depth of an antenna specialist; however, since antenna performance and arrangements are closely intera ive, the naval architect needs knowledge of electromagnetic theory. The depth of knowledge should include an understanding of classical solutions of the wave equation for the field, the antenna impedance, the currents induced in structures, and the impact of antenna illumination on antenna patterns.

TOPSIDE DESIGN

Aspects of topside design have been discussed earlier. A few additional comments are included here.

Sail Area

The growth in sail area has been discussed by Sarchin and Goldberg [8] on page 449 of their paper on stability. Large sail area requires added beam for stability in high wind. Large sail area implies a large radar cross section. Large sail area implies a large target for attacking antiship missiles.

Antennas

The location and performance of antennas is part of topside design. The topic has been discussed earlier.

Combat Information Center, CIC

The details of the layout of CIC, the displays within CIC, the communication networks both external and internal, and the manning levels for CIC for different watch conditions are the realm of the human factors engineers, the

Naval line officer, and the electronics engineer. Christofferson [35] presents an interesting commentary on CIC design from the point of view of the professional Naval officer.

Once again, however, a strong interaction exists between arrangements and CIC design. The volume requir or CIC depends on design of CIC.

One interaction which was mentioned previously was the location of CIC relative to vulnerability.

Bridge

The introduction of computers and displays to improve effectiveness of conning and to reduce manning on commercial ships has been progressing rapidly; see the articles by Ware [36], Rinaldi [37], and Sorenson and St. Germain [38]. The United States Navy has initiated work on the integrated bridge design, IBS. Cox, Puckett, and Gowen [39] discuss various functions incorporated into IBS. Puckett and Sniffin [40] report on "at-sea" tests of IBS. Read [15] comments on the automated bridge system, ABS; his comments were NOT favorable. ABS is an example of the "Behemoth Syndrome" according to Read [15].

The reason to introduce the discussion of the IBS is that changes in bridges may occur in the United States Navy. The changes have an impact on arrangements. Direct changes in arrangements due to IBS include size but not location. Indirect changes to arrangements result from reduced manning. Reduced manning decreases, obviously, the space required for crew along with the extent of hotel services.

Cut Out Zones

Cut out zones are a geometrical factor which are determined by geometry of superstructure and weapon locations. Radar blockage, which was presented earlier, is analagous to cut out zones.

Combat system effectiveness is degraded by cut out zones. Fire power at certain relative angles is nonexistent.

Cut out zones should be an easy factor to quantify for an arrangements figure of merit.

Distribution of Mass

Besides the geometry of topside design, the distribution of mass is a consideration, KG and moments of inertia have been discussed. The distribution of mass influences the design of the hull structure.

CREW/HABITABILITY/MANNING

Manning requirements have a major impact on arrangements. A model for predicting manning requirements has been developed by Plato [41]. The manning requirements specify not only numbers but rank and rate. Further, specialities are given, i.e., how many boatswain mates, etc.

Habitability is reported frequently as a function of the volume per man available within the ship. Habitability is important since crew performance depends on physical and psychological fitness.

Combining habitability standards with the distribution of rank and rate within the manning schedule, one obtains the variables important for arrangements. Living quarters should be remote from noise sources. For senior petty officers, the habitability standards are higher.

The arrangements figure-of-merit should account for quality of living spaces. Quality depends on noise level, access, air conditioning, and similar factors.

ACCESS

Access is an arrangements factor which has been discussed by Hope and Carlson [42]. Access has been modeled adequately. In fact, the models should be useful guides for the modeling of other arrangements factors.

Arrangements and maintenance philosophy are interrelated; see the paper by Guido and Light [43]. Allocation of "in-place" maintenance clearances is an arrangements factor which must be monitored and controlled as the ship design and construction progresses.

Read [15] gives a report card on arrangements in DD-963 class and LHA-1 class. The waste heat boiler in DD-963 was one item mentioned.

AVIATION SYSTEMS ON SURFACE SHIPS

The combat system performance of surface ships is enhanced greatly by helicopters. The helicopter is a valuable component for ASW. Importance of the helicopter is not restricted to ASW. OTH targeting can be accomplished by helicopter. Limited capability exists for airborne early warning.

The helicopter is not the only aviation system for surface ships. RPV have been discussed in previous sections. Vertical attitude take-off and landing, VATOL, aircraft may someday be commonplace on surface ships; VATOL has been discussed by Eilertson [44]. One advantage of VATOL is the use of the edge of the deck.

Aviation systems have an extensive impact on arrangements. Hangar, maintenance facilities, aviation fuel, living space for aviation department personnel, communication and navigation antennas, expanded CIC to accommodate aviation control, and storage of aviation spares and weapons must be provided. Although Jolliff's [45] article is oriented toward CV or CVN design, many comments and facts are transferrable to surface ships. Many items from Tables I and II of Jolliff's article apply to a surface ship with an aviation system aboard.

In regard to helicopter launch and recovery, the ship's superstructure has an influence. The wind and air flow over and near the helicopter pad is important. Downstream of the superstructure, large turbulent eddies and

vortices occur. With the relative wind on the port bow, the turbulent air moves away in the starboard quarter. The extent and intensity of turbulent wake depends on superstructure shape and size.

WEAPONS

Destroyer class warships carry a wide variety of weapons to meet the needs of multimissions. Various weapons are discussed now from the point of view of arrangements.

Guns

Guns play a secondary role to other weapons. In AAW, missiles are the main defensive weapon. In SUW, the antiship missiles, such as Harpoon or Tomahawk, are the main offensive weapon. Guns are secondary. In ASW, torpedoes launched by the ship or helicopter are the main weapon. ASROC is also a primary ASW weapon. Guns do not play a role in ASW. In amphibious support or gunfire support mission, guns become a major weapon.

In the competition for deck area and enclosed volume, guns are relegated to a secondary priority. Fortunately gun systems have flexibility for location.

Three factors should be considered relative to guns. First, the capability of girst generation guided projectiles greatly enhances gun effectiveness. Second generation guided and propelled projectiles will be, in essence, gun launched missiles. Second, on the first and second day of the BIG war, missiles will be fired at a tremendous rate. Destroyers have a limited magazine capacity for missiles. On the third day of the war, guns may be the only defensive or offensive weapon with rounds in the magazine. Third, guns of the Phalanx variety provide extremely fast response in the last ditch defense. Guns will always be a short range weapon compared to missiles.

With these comments in mind, guns and gunnery may have a renaissance.

Some of the factors relative to guns and arrangements are illustrated by Figure 1, which is reproduced from Eckhart [46]. Looking at Figure 1, one can identify various inputs influenced by arrangements. One example is hull flexure which has been discussed already. Lever arm velocity is another term dependent on arrangements.

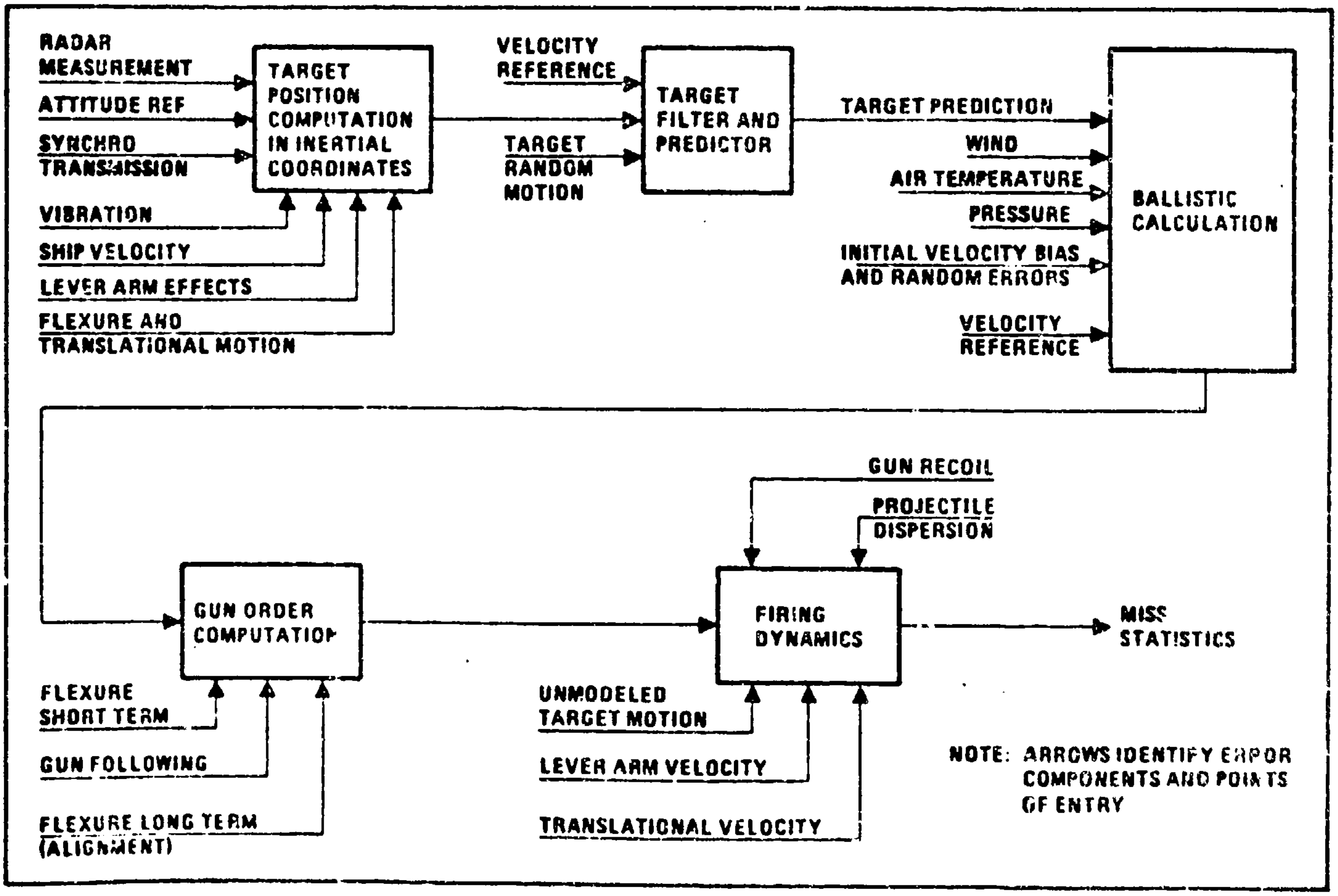

Figure 1. Gun Fire Control Mechanization Error Flow. (From M. Eckhart, Jr., "A System Engineering State-of-the-Art Equal to Modern Warship Design," ASNE Journal, Vol. 90, No. 2, April, 1978, p. 133.)

Magazines and Hoists

Magazines for gun projectiles should be near the gun mount served by the magazine. From the point of view of vulnerability, a magazine should be in a

protected region of the ship. Magazines may be located below the waterline. Hence, hoists are required. A magazine should be vertically below the gun mount if a hoist is used.

Likewise for missiles, the magazine should be near the launcher.

Missiles and Launchers

A variety of missiles is used by destroyers. The Terrier and Standard Missile are current AAW missiles. The NATO Sea Sparrow is another AAW missile. Under development is the Rolling Airframe ASMD missile. Sea Phoenix was considered seriously at one time; see Tarpgaard [47].

Mentioned previous were Harpoon and Tomahawk. Both missiles strengthen a surface ship's offensive capability.

Several launchers are used by the Navy. Rail launchers include MK26 with two rails and MK13 with a single rail. Intercept ranges are longer and intercept times are shorter with rail launch as compared to vertical launch system, VLS. The VLS offers significant advantages. Rail launchers are heavy and require considerable volume for the magazine. Rail launchers impose very large transient electrical loads on ships' generators. The VLS is the magazine and launcher in one module. Volume is reduced. Electrical load is near zero.

Cannister launchers are used for Harpoon and Tomahawk. In this case, the magazine is located above decks. The warheads are exposed to light weapons.

In regard to arrangements, rail launchers require large volume and are heavy. The possible locations for a rail launcher are limited. VLS offer more flexibility in regard to location.

The complete missile system includes fire control radars, computers, weapons displays, weapon control system, magazine, launcher, and strike-down apparatus.

As discussed earlier, arrangements influence cut out zones for missile launching.

Since missiles may be one of the largest items transferred during replenishment at sea, missile size determines the deck area for UNREP or VERTREP.

Torpedoes

The major ASW weapon for destroyers is the torpedo. Torpedoes may be larger than missiles as an item in underway replenishment. If so, the comments above about deck area for UNREP apply to torpedoes instead. Torpedoes, as is well known, are launched from torpedo tubes. Torpedoes have limitations on launch elevation and speed of launch platform. The height of the torpedo tubes above the water is an arrangements constraint.

Incidentally, in regard to torpedo tubes, Read [15] terms some of the new designs "behemoths."

Advanced Weapons

Not of concern today are the weapons of the future. High energy lasers, HEL, may become operational on United States Navy ships. A special set of arrangement criteria will apply to HEL. Some HEL use toxic gases for fuels. Fuel storage and handling will require careful consideration.

Another advanced weapon is charged particle beams which have been discussed negatively by Parmentola and Tsipis [48]. A rebuttal was written by Wright [49]. Charged particle weapons require pulses of very high voltages, 500 to 20000 MeV, and large currents, 10^5 to 10^{10} amperes. Instead of current, the electrical charge per pulse is frequently used. The charge per pulse is in the range of 10 to 100,000 microcoulomb/pulse.

COMPUTERS

Computers are an essential component of a combat system. The relationship between arrnagements and computers needs discussion.

Computers allow a variety of modular approaches to weapon system control and design. In lieu of a large central computer, smaller computers can be distributed where the computation load occurs. A series of articles discuss one option relative to computers; see Carruthers [50], Kuhns [51], Williams and Anderson [52], Thomas [53], and Carruthers [54].

A large central computer requires an appropriate environmentally controlled space. Distributed computation eliminates the volume and space for the computer compartment. Arrangements are thereby affected by decisions about computers.

Many articles have been written about software and software management. The article by Gallant [55] provides considerable insight to check out of computer programs.

MULTIPLEXING

Multiplexing is a method to decrease the amount of cables on board ships. The shipboard data multiplex system is discussed by Wapner [56].

Cables penetrate watertight bulkheads. Cables require conduits which consume space within the ship. Cables also require terminal boards and junction boxes. Each of these factors relates to arrangements.

Multiplexing offers advantages of saving weight, space, and cost. Further, a few redundant cables along with multiplexing provide greatly improved survivability.

SHIP SIMULATIONS

In the development of combat systems, land based test sites, LBTS, are used. Duke [57] discusses the LBTS for DD-963 class, Dalla Mura [58] discusses LBTS for AEGIS, and Asher [59], the FFG-7.

A land based test site is analogous to a breadboard for an electronic circuit. For a breadboard, components are wide spaced without concern for final packaging. Components can be changed easily, and test points are accessible. The breadboard provides a tool to develop the functional aspects of the circuit. Once the electronic circuit functions properly, the design of the circuit board and packaging can proceed. At this point stray coupling and interference may become important as components are squeezed together.

The final step of designing a circuit board and the packaging is analogous to arrangements and installation on the ship. Problems can occur.

Land based test sites provide a hardware simulation of the combat system. As stated by Frost [60], the test sites need to simulate all the actions and stresses which the combat system will encounter later. If this is done, the problems which occur during operational testing and subsequent fleet use should be reduced. Frost [60] states that LBTS are an absolute requirement for proofing technical performance, computer software, and integration techniques of complex systems.

To what extent can LBTS be used to assess arrangements?

Returning to the analogy of the electronic breadboard, a precision duplication of arrangements would reduce flexibility and impede progress. Perhaps a LBTS could be designed with two levels of simulation. The first level is for functional testing only. The second level includes arrangements and functional testing.

Section II has provided a list of the many variables to be considered in warship design. The relation between the various quantities and arrangements has been discussed briefly. One should now consider approaches for analysis of arrangements. The approach should lead to a figure-of-merit, or, more likely, a set of figures-of-merit for arrangements.

III. MODELS FOR ANALYTICALLY TESTING ARRANGEMENTS

Arrangements need to be evaluated during conceptual design and preliminary design. At these points in the cycle, hardware is far downstream in time. Hence, an evaluation of arrangements at these points in the design cycle must depend on an analytical technique. By analytical technique, one includes numerical modeling using computers.

Returning to the mass of information presented in Section II with the thought of organizing and correlating the various facets and features, some observations are relevant.

When confronted with the mass of variables, one should break the problem into digestible chunks. The nomenclature of "digestible chunks" is not elegant, but it does avoid any semantic confusion. The next step is to define interactions between chunks. In many discussions and technical articles, the interactions are portrayed by block diagrams with blocks connected by light solid lines, heavy solid lines, dashed lines, dotted lines, etc., all with arrowheads. These block diagrams, which are referred to frequently as "wiring diagrams," are very meaningful to the author. Block diagrams border on art; art gives an impression and generates an emotional response.

The interaction between components needs to be defined quantitatively. One really does not understand a problem until a feature or aspect can be reduced to a number.

The concept of independent variables and dependent variables is used extensively in mathematics. The functional relation

$$z = f(x,y) \tag{3}$$

illustrates the concept. The dependent variable is z; both x and y are independent variables. Equation (3) can be rearranged in the form

$$F(x,y,z) = c \tag{4}$$

The form of equation (4) more closely represents the warship design problem. A set of values of x, y, z exists such that when the variables are related by a function F, the result is a constant c. In terms of warship design, x, y, and z represent the design variables, e.g., length, draft, propulsion power, etc. The equality of equation (4) represents convergence of a design to meet design goals.

Considering arrangements, one wants to make x in equation (3) an arrangements variable. In that case, z becomes one of the measures of ship performance; for example, z might be combat system reaction time.

Of particular interest is the ability to differentiate equation (3) to form

$$dz = \frac{\partial f}{\partial x}\, dx + \frac{\partial f}{\partial y}\, dy \tag{5}$$

The quantities $\partial f/\partial x$ and $\partial f/\partial y$ are the design sensitivities. For the example being discussed here, $\partial f/\partial x$ becomes the change in combat system reaction time due to a small change in arrangements.

Appendix B is one attempt at a formal mathematical approach to quantifying arrangements. If the attempt were successful, the results would appear at this point; however, since the attempt does not offer much progress, it appears as an appendix.

ARRANGEMENTS FROM OVERALL SHIP DESIGN

An evaluation of arrangements using overall ship design has several advantages. As the discussion of Section II indicates, the design of a ship involves many interacting parameters which must be balanced. To introduce arrangements into overall ship design, variations in arrangements must be

introduced as a set of variables. The advantage of the approach is that arrangements become one of the design variables. Interaction between arrangements and other design factors occurs in a logical manner.

As discussed previously, arrangements consist of two distinct parts. One part involves geometric relationships; for an example of geometric relationship, consider which component is placed in front or behind another component. The other part of arrangements is quantitative, e.g., separation of two components is five feet.

If arrangements are introduced as variables, the design process, which includes techniques of optimization, will yield the optimum set of values for the arrangements variables.

The concept of convergence of a design merits additional discussion. To define convergence of a design, one can define what nonconvergence means. A warship has certain design goals such as payload, endurance, cruise speed, and flank speed. A ship with a given length, beam, horsepower, etc., may meet the specification for payload, cruise speed, and flank speed; however, the design does not meet the specification for endurance. The design is not a converged design.

By increasing displacement, all four design goals can be satisfied. The result is a converged design. The designer might stop at this point; however, a better choice of design independent variables may yield a less costly design which meets performance specifications. The process of finding the "better choice" is known as optimization. Optimization requires a measure of success, i.e., the design is optimized with respect to some quantity. In this case, the words "less costly" imply that the measure of success was cost. Optimization also involves constraints. For example, the warship may be designed with the constraint that radar cross section for the ship cannot exceed 5000 m^2.

Relative to design convergence, assuming known design goals, several questions occur as follows:

What quantities vary to permit convergence?

What quantities remain fixed?

What are the design inputs?

What are the design outputs?

Relative to design optimization, additional questions occur as follows:

What is the measure of success?

What are the design constraints?

Consider these questions relative to arrangements. An example best illustrates how arrangements become part of design.

For simplicity, assume that the warship has one gun, one search radar, and one F/C radar. The design goals for the warship are as follows:

speed

payload

endurance

weapon accuracy

reaction time

The design inputs, which are independent variables, are as follows:

5"54	length
SPS-48 radar	beam
MK-86 F/C	draft
LM 2500 gas turbine	propeller diameter
single screw	mast height, y

distance from crew living compartment to gun mount, z

distance separating superstructure from gun mount, x

The variables related to arrangements are x, y, and z. Arrangements consist of two features. One feature is the relationship of parts. In this example, the gun mount is in front of the superstructure, and the crew compartment is below the main deck aft of the gun mount. These are relationships as specified by "in front of," "beside," "above," etc. The other feature is quantitative, i.e., numerical values for x, y, and z.

The design outputs are the values of the performance parameters which are also the design goals. The output consists of speed, payload, etc. Assume the design has not converged.

Certain inputs remain fixed; for example, the hardware (e.g., 5"/54) remains fixed in mass, volume, and location of the center of gravity. The relationship aspect of arrangements remains fixed. The creativity of the design is reflected by the relationship aspect of arrangements. All other inputs, i.e., length of the hull, beam, x, y, z, etc., can be varied to achieve convergence.

Assume reaction time exceeds the specified value. Reaction time consists of a sum of individual times taken in series. The time involves changing from one readiness condition to another readiness condition. The time for hand off between search and fire control radars is another element in overall reaction time. Suppose the ship is attacked from the stern; to bring the gun to bear on the threat, the ship must turn. Turning time is added to the summation of time which becomes reaction time.

To decrease reaction time, each element in the summation is examined. By increasing the distance, x, which is the distance separating the superstructure and the gun mount, the cut out zone is made narrower. The maneuver time is reduced. Turning rate can be increased by changing hull length; however, a change in hull length is a major decision.

To decrease reaction time, the length z can be decreased. The crew for the magazine and ammunition handling room has a shorter distance to travel.

The simple example contains the essence of one approach for introducing arrangements into the design process.

In summary, the features of the process are as follows:

- The relationship aspect of arrangements is an input by the designer and remains fixed during the iterations leading to convergence.
- The quantitative aspect of arrangements is an input and varies during the iterations leading to convergence.
- The converged design becomes a baseline from which departures are made leading to an optimized design; during optimization, relationship remains fixed while quantitative arrangements vary.
- The design process is repeated for each different perturbation in the relationship aspect of arrangements.
- The key to this approach is meaningful description of arrangements through quantitative variables.

INFLUENCE OF ARRANGEMENTS ON SUBSYSTEMS

To evaluate arrangements, the influence of a particular arrangement on a specific major subsystem can be determined. A list of major subsystems can be written as follows:

1. hull structure
2. main propulsion plant
3. electric plant
4. helicopter

.

.

.

30. CIC
31. bridge

Each subsystem has been assigned a number. As is done in Appendix B, define a quantity P_i which is the performance of i'th major subsystem. For example, P_4 is the performance of the helicopter; P_4 itself may be an array of performance parameters. P_3 is the performance of the elec' .c plant; P_3 consists of the following:

power output

frequency stability

generating efficiency

mass

Define a quantity A_j which characterizes the arrangement of the j'th major subsystem. A_j is composed of several geometrical variables such as area, volume, location, shape, and length. Location of centroid can be specified relative to reference axes. Likewise, location of center of gravity can be specified relative to the same axes.

Define an influence coefficient I_{ij}. The quantity $I_{ij}A_j$ is the performance of i'th subsystem as determined by the arrangement of j'th subsystem. An equation can be written which emphasizes the impact of all subsystems on each other; the equation is

$$P_i = \sum_{j=1}^{31} I_{ij}A_j \tag{6}$$

As shown by Appendix B, equation (6) cannot be interpreted literally as a linear matrix equation. Equation (6) emphasizes the fact that performance of i'th subsystem depends on arrangement of all subsystems. The influence "coefficients" may consist of a verbal description. One would much prefer to quantify I_{ij}.

Expanding equation (6) gives, as an example,

$$P_3 = I_{31}A_1 + I_{32}A_2 + I_{33}A_3 + \cdot \cdot \cdot \cdot + I_{3,31}A_{31} \tag{7}$$

The quantity I_{31} is the influence of the hull structure on the electric plant; if no interaction exists, I_{31} is zero. The influence coefficient I_{32} is the influence of arrangement of the main propulsion plant on the performance of the electric plant. I_{33} is the performance of the electric plant as determined by its own location. If the electric plant is near the keel, pumping from fuel tanks in the bilge is easier. Near the keel, the electric plant needs a more sturdy foundation to pass shock tests. Near the keel, the intake and exhaust ducts are longer; greater pressure losses occur decreasing generating efficiency. I_{33} should incorporate the preceding considerations.

The merit of equation (6) is that interactions are not overlooked. Further, equation (6) forces attention to the various influence coefficients, I_{ij}; the designer systematically examines each interaction.

Obviously, the I_{ij}, which are essential to the approach, are ill defined. Considerable additional work is needed.

Using this approach to arrangements, how does the designer know when he is successful?

The approach yields, in this example, 31 different sets of values for performance parameter P_i. A figure-of-merit for arrangements, F_a, can be based on the P_i. For example

$$F_a = \sum_{i=1}^{31} P_i \tag{8}$$

Another figure-of-merit could be defined as

$$F_a = \sum_{i=1}^{31} W_i P_i \tag{9}$$

where W_i are weighting factors.

COMBAT SYSTEM PERFORMANCE ANALYSIS

War, battles, and combat are statistical in nature. The probabilistic nature of combat must be incorporated in the analysis of a combat system. Having made this statement about combat, two questions arise. First, at what point in the life cycle should the probabilistic combat analysis be conducted? Second, what is the connection, if any, between arrangements and the randomness of combat?

Design is definitive. The length of a ship is 459.2 feet. Neglecting production tolerances, the length is not random. Combat is random. Every battle has a different outcome. Each event or trial gives a different result. When events are repeated many times, a pattern evolves. From the pattern, the statistician extracts a mean, a standard deviation, and higher moments. The mean is a definite number. Likewise, the standard deviation is a definite number.

For a combat system, can one specify definite numbers which characterize the combat system, the threat against the system, and the environment in which the battle is fought? The answer is affirmative. The combat system engineer and the combat system analyst can specify definite performance values for the combat system. Given the specific weapon suite, three quantities almost completely specify the combat system. These are

reaction time

accuracy of weapons

ability to handle N multiple targets

Assume that the weapon suite is specified, the sensors are known, the threat is defined, and the scenario is described. Can one arrive at meaningful values for the reaction time, required accuracy, and specification on number of simultaneous targets to be handled?

If the answer is yes, then one has denied any connection between the ship platform and the results of the engagement; any connection between arrangements and combat system performance is denied. If the answer is no, as it most assuredly must be, then the interaction between arrangements and combat system performance must be accounted for.

During the warship design process, the conceptual ship must fight a conceptual engagement. Outcomes of the engagement analyses establish the merit of various ship designs.

To determine the influence of arrangements, two different ships having different arrangements can fight the same threat. For example, suppose a ship has only one MK 26 missile launcher. In one design, the launcher can be forward. For the other design, the launcher can be located aft. This is an example of varying the relationship aspect of arrangements. Any difference in the performance of the combat system can be traced to arrangements.

One model for testing combat system performance will now be discussed.

IV. MODEL FOR ASSESSING THE ROLE OF ARRANGEMENTS IN COMBAT SYSTEM PERFORMANCE

To illustrate the model, a specific example will be described along with commentary. The model uses a Monte Carlo approach to the engagement; see Gellert, Justner, Hellwich and Kastner [61]; Considine [62], or Bartlett [63].

SCENARIO

The scenario states the environment and circumstances under which the engagement or battle occurs. Depending on the scenario, the warship may be steaming under wartime conditions.

For the example, a DD is an escort to a convoy. The convoy is attacked by antiship missiles.

THREAT

The outcome of a battle depends on the weapons which the enemy employs. Details about the threat include the following: number, duration of attack, speed, flight profile, radar cross section, IR signature, relative attack azimuth, warhead weight, guidance, evasive maneuvers, and fuzing.

For the example, the convoy and DD are attacked by 10 AS-6 Kingfish missiles and 9 SS-N-7. Since the DD is the only AAW ship in the convoy, all missiles are targeted for the DD.

The random variables relative to the threat must be specified. The AS-6 has two flight profiles; one is diving, and the other is sea skimming. The probability was assumed to be 50-50 for dive or sea skim. The attack azimuth was random with a uniform distribution over the 360°. The streamtime is random; streamtime is the time interval between attacking missiles. Streamtime statistics may be based on a Poisson distribution function. In any event, a probability distribution must be specified for streamtime; see Johnson, Whitney, and Nash [64].

Additional random aspects of the threat include statistics of mass distance, probability of fuzing, and probability of detonation. Warheads may disintegrate without exploding upon impact against a girder, rib, or other sturdy member of the hull.

SENSORS; RADAR

The information necessary for the engagement is probability of detection, P_d. For a given radar, P_d depends on cross section of the threat, height of the antenna above the water, and atmospheric effects. Atmospheric effects may cause radar "holes" and radar "ducts." In certain areas of the world, ducting occurs more often than one might first estimate. Rimer [24] discusses ducting relative to OTH targeting.

The radar horizon is determined by the altitude of the target and the height of the antenna. Frequently P_d jumps from zero to unity when a sea skimming missile emerges over the horizon.

SENSORS; ELECTRO-OPTICAL

Once again the P_d curves are needed for the various EO sensors which may be used. P_d depends on the IR signature of the target. Due to aero-dynamic heating, high-Mach number targets have a large infrared signature. The P_d curves depend on background noise. The ship can generate background noise in the infrared; consequently, performance of an IR system depends on location of the IR sensor.

IR search and track systems are important when conditions of emission control, EMCON, are imposed. The scenario determines whether or not EMCON is in effect.

EO sensors other than infrared sensors may be used.

HAND OFF FROM SEARCH RADAR TO F/C RADAR

Typically the antenna pattern of a search radar is a large fan beam. The F/C radar uses a circular antenna of sufficient size to give a very narrow pencil beam. The search radar can locate the target only within the bounds of the antenna pattern. The F/C radar with a much smaller beam must search within the search radar antenna pattern. A probability of successful hand off from search to F/C radar can be calculated.

Pulsed array radar serves both functions of search and track. A precision track is necessary for the fire control solution. Phased array radars have greater capability and more flexibility than combined search and F/C radars. See Duffy, Cain, and Cown [31].

ELECTRONIC WARFARE

Use of chaff or IR decoys is one form of electronic warfare. In the event one of the threats leaks through the defense, chaff and IR decoys can be deployed. The probability of spoofing is a function which is needed for the engagement. A variety of modes can be used for chaff including the dilution mode, centroid (seduction) mode, and dump mode.

If the attacking missile is spoofed, the miss distance will be large enough to prevent damage to the ship.

WEAPONS; GUNS

The kill probability, P_k, of three types of projectiles needs to be calculated. There are as follows:

unguided AAW rounds; 5", 76 mm

guided projectiles; 5"

unguided penetrators; 30 mm, 20 mm

The guided projectiles are used with 5"/54 gun mounts as are the unguided AAW projectiles.

For each threat, a separate P_k curve is needed. One can think of a matrix. The rows of the matrix are the different gun projectiles; for the case being discussed here, there are five different projectiles. The columns of the matrix are the different threats; for the case at hand, there are two threats, AS-6 and SS-N-7.

The unguided penetrators that have kinetic energy as a kill mechanism use closed-loop spotting. The miss distance for closed-loop spotting needs to be modeled.

For guided projectiles, the miss distance depends on guidance scheme and the remaining kinetic energy of the projectile. Projectile kinetic energy decays as range increases. Kinetic energy is consumed by maneuvers. Hence, as range increases, the ability to maneuver decreases.

<u>WEAPONS</u>; <u>MISSILES</u>

Once again P_k for the missiles must be determined. Two missiles were considered. One was characteristic of Standard Missile-2, SM-2, and the other was characteristic of the Rolling Airframe Missile, RAM. RAM has a 5" diameter warhead.

P_k depends on miss distance and warhead size. P_k, of course, depends on the target. For miss distance statistics, the missile guidance method is considered.

For both gun projectiles and missiles, the time-of-flight to intercept is an important quantity. For a simple model, an average flight velocity can be used. For a more realistic model, the changes in velocity due to drag and changing altitude can be modeled.

WEAPONS; LAUNCHERS

Time is important. The time to load, the time between launches, and the time to slew are included in the model of the launcher. A small probability of launcher failure is inserted.

For vertical launch system, VLS, the time to intercept is complicated by the vertical climb and initial turn. Also, the VLS causes a loss of energy due to the initial turn.

PROBABILITY OF SURVIVAL

Consider a raid with N attacking missiles. The probability of survival, P_s, is given by

$$P_s = [1 - P_t + P_t P_w - P_t P_n P_w]^N \qquad (10)$$

where P_t is the probability that the threat kills own ship, P_w is the probability that own ship weapons kill the threat, and P_n is the probability of a threat leaking through to own ship. Equation (10) is discussed by Johnson, Whitney, and Nash [64].

The probability of leak, P_n, can be modeled; an equation for P_n is

$$P_n = 1 - [e^{-N}(1 + \frac{N}{T/T^*})]^{1/N} \qquad (11)$$

where T is the average total engagement time for N threats and T* is the average reaction time for the combat system.

Equations (10) and (11) are useful for gaining insight to saturation attacks. However, the model is too simple. For example, use of P_t requires an assumption that the ship is or is not killed by a threat. Gradation in damage may occur.

SURVIVABILITY/VULNERABILITY SIMULATION

In a saturation attack some of the attacking missiles will leak through the defenses. A method for assessing the damage is required. A model for survivability/vulnerability simulation consists of the following steps:

- hit location—random
- penetration/breakup
- explosion damage
- functional impairment
- probability of loss of capability

Hit location is random. Frequently, the missile guidance system aims for the centroid of the projected area. A Gaussian distribution can be used for miss distance from the aim point. The point of impact is determined for a particular case by use of the miss-distance distribution function and random number generation.

the point of impact and missile trajectory are known, penetration is [illegible]ermined. If the warhead hits a frame or girder, it may disintegrate. If the warhead does not disintegrate, hitting a frame will cause deflection of the path of the warhead.

A modern antiship missile will pass completely through a ship if it does not hit a substantial item of machinery. The article by Meller [65] shows the [illegible]oran [illegible] emerging from the other side of the target ship. The warhead can be detonated by a variety of fuzing techniques. Fuzing has a set of its own statis[illegible].

Based on the pene[illegible]ation and fuzing model, the location of the warhead detonation is known. The Kormoran warhead uses a P-charge warhead. On

detonation of the main charge, thick, cup-shaped eel plates welded into the warhead casing are propelled outward at high velocity. The steel plates can penetrate up to seven bulkheads; during tests some plates were found in compartments separated by seven bulkheads from the charges. The paths of the steel plates are statistical.

A P-charge is similar to a shaped-charge except that the cone angle is large, giving an almost flat plate.

In assessing explosion damage, a variety of possibilities exist. Equipment within the compartment may be useless due to blast, shock, fragments, or heating. Cables may be severed. Piping may be ruptured. Ventilation ducts may collapse or may be punctured.

For the P-charge, a certain number of steel plates are projected outward. If a cable happens to coincide with or intersect the path of one of the steel plates, the cable can be considered to be cut. Projected area of components as seen from the warhead can be used to estimate probability of damage.

Once damage has been established, the impairment of function must be assessed. If the waveguide is cut, the associated radar is removed from action. Search or track function is degraded. For the remainder of the engagement, the ship operates in a degraded mode.

If the damage included one diesel generator set, the ship must adjust use of power to match generation capacity. Several such items with loss of capability are factored into the consideration of functional impairment.

The probability of loss of capability can be determined if the engagement is repeated many, many times. A probability that the waveguide will be cut can be generated.

COMPUTERS

Computers are specified in terms of throughput, which is the number of calculations per unit time. Other specifications include memory size and clock time for the central processing unit.

To select a computer, the combat systems engineer lists all components which require computational capability. The type of calculations to be performed is identified. Examples of type of calculations include matrix inversion, fast Fourier transform, matched filter, and numerical integration. The allowable time for the calculation is determined. Using this information, an estimate of space in the processor, in bytes, is made. Memory requirements, given in bytes, are also estimated.

The computer must provide real time computation during an engagement without becoming saturated. As shown in the paper by Johnson, Whitney, and Nash [64], the number of different sequences of threats to be calculated is eN! for an attack with N threats. Stated in different words, if one wants to calculate all possible ways of engaging N threats, the number of engagements to be calculated is eN! Real time, explicit, calculation becomes impossible even for small N.

SEQUENCE OF EVENTS

With the information described above, one can proceed with the engagement. The sequence of events is listed in Table III.

The engagement as described here has not been programmed for the computer. The engagement has been exercised many times manually. As a side comment, the human being is a very good computer; the only difficulty is that the human is slow, makes mistakes, and gets bored after a few engagements!

Table III. Sequence of Events for an Engagement

CHANGE OPERATING CONDITION

Change to general quarters

INITIATION OF ATTACK

Determine streamtime for threats; use distribution curves
Determine azimuth
Determine dive or sea skim

SEARCH

Detection (radar); use P_d curves
Detection (IR); use P_d curves
Establish coarse track
Identification/IFF
Evaluate/prioritize/threat assessment
Assignment of F/C radar
Designation of weapon
Hand off to F/C radar

ACQUISITION

Establish fine track
Generate F/C solution
Load/slew launcher
Preset missile/select missile mode

LAUNCH/FIRE

Verify engageability of weapon
Verify operability of weapon
Boost
Midcourse command
Terminal/target illumination

INTERCEPT

Damage assessment; use P_k curves
Register kill/miss
Release weapons/F/C radar
(OR for miss)
Select weapon
Launch

Table III Continued. Sequence of Events for an Engagement
LEAKING THREAT
Attempt spoof using IR decoy or chaff; use curves for probability of spoof
Successful spoof/ignore threat
Unsuccessful spoof
Determine hit location
Determine penetration
Explosion damage
Determine functional impairment
Factor impairment into ship capability for remaining threats
CYCLE THROUGH REMAINING THREATS

When exercised manually, the engagement model requires several diagrams. One diagram shows range as a function of time. Own ship is placed at range equal to zero. On the range/time diagram, all threats can be shown along with weapons in the air. The intercept range follows graphically from the diagram.

Another diagram tracks the various components as a function of time. The diagram shows when a weapon or a radar is busy and when it is available for use. The diagram shows time to reload, time to slew, etc.

To obtain probability of survival, probability for out-of-action, etc., the engagement must be repeated many times. This cannot be done manually.

Returning to the arrangements figure-of-merit, the probability of survival becomes a figure-of-merit.

The model described in this section treats only AAW. All other missions of the ship must be exercised, i.e., ASW, GFS, and SUW. Also the model is for a defensive scenario. The ship must be exercised when on the offensive. When the ship has the offense, the probability of kill of the target becomes a figure-of-merit.

V. SUMMARY AND CONCLUSIONS

Arrangements, which are geometrical quantities, have two aspects. One aspect deals with relationship between components, e.g., component A is in front of component B and below component C. The other aspect of arrangements, which can be made quantitative, involves the geometrical quantities of area, volume, location, length, and shape.

Certain consequences of an arrangement lend themselves to precise formulation. An example is stability which involves the distribution of mass. Other consequences of arrangements are less precisely described. An example is the location of CIC. Antennas are a special case in arrangements. A strong interaction occurs between antenna performance and arrangements; see Appendix A. The equations for the interaction are well known; solution of the equations requires extensive numerical calculation or precise brass models. Geometric detail must be well defined.

Any figure-of-merit for arrangements is an arbitrarily defined quantity. This does not mean useful figures-of-merit cannot be defined. It does mean any figure-of-merit does not have the impact of the first law of thermodynamics.

Several approaches exist to evaluate arrangements. One approach is to define and quantify certain arrangement variables. The arrangement variables are introduced into the overall ship design process. Arrangements have two geometrical aspects: relationship and quantitative features such as area. The overall ship design approach treats the quantitative aspect.

Another approach is to consider interaction among subsystems. The interaction is due to arrangements. A method for systematically examining the numerous interactions has been suggested. The method uses the influence coefficients, I_{ij}.

A third method of evaluating arrangements along with the other facets of design is to simulate combat engagements. The probabilistic nature of combat forms the core of the model. A simulation of a combat engagement permits comparison of two warships. The relationship aspect of arrangements can be evaluated. When comparing two warship designs, both designs are presumed to have incorporated the quantitative aspect of arrangements in the design process. Each design is optimized. The difference in the two designs is one c relationship of components.

The comments in this paper are more in the nature of suggestions. The model for simulation of a combat engagement has been exercised several times manually. The model treats only AAW. The other models and approaches for arrangements are more in the nature of proposals for a new technique.

APPENDIX A. AXIAL DIPOLE ANTENNA WITHIN A CORNER REFLECTOR

One of the problems which can be solved is a dipole antenna located near a corner reflector. The corner reflector is comprised of two large flat metal sheets which form a "V." The z-axis lies along the intersection of the metal plates. The metal plates could be a corner formed by superstructure.

The dipole antenna is located at point $Q(\rho_0, \phi_0, z_0)$; the axis of the dipole is parallel with the z-axis. The double arrows in Figure 2 represent the dipole. Any typical field point is represented by point $P(\rho,\phi,z)$.

The electromagnetic field is wanted in the volume $0 \leq \phi \leq \psi$. Within the volume the electrical properties are uniform with values ε for electrical permittivity and μ for permeability. The dipole antenna has an electric moment of Idz_0.

The electromagnetic fields can be expressed in terms of the Hertz vector, which in this problem has only a z-component. The z-component of the Hertz vector is designated as Π. For a discussion of Hertz vector and boundary conditions for electromagnetic waves at a metal wall, see Chapter 1 of Stratton [33].

The following development follows closely that of Wait [34].

Since the excitation is due to a dipole, the electric field components of the wave are given by

$$E_\rho = \frac{\partial^2 \Pi}{\partial \rho\, \partial z}, \tag{12}$$

$$E_\phi = \frac{\partial^2 \Pi}{\rho \partial \phi\, \partial z} \tag{13}$$

and

$$E_z = \left(k^2 + \frac{\partial^2}{\partial z^2}\right)\Pi \tag{14}$$

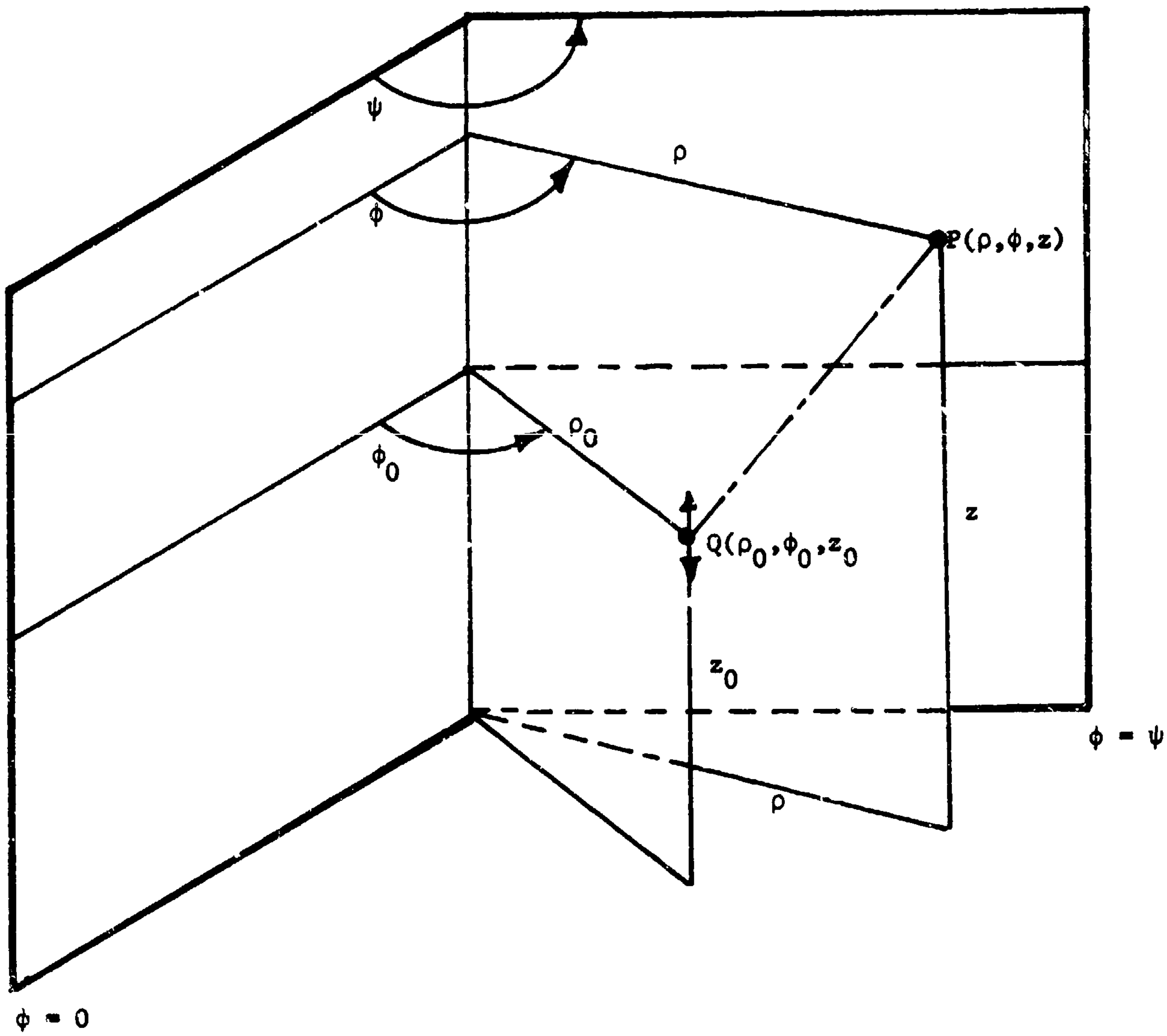

Figure 2. Corner reflector formed by two metal plates at an angle ψ. A dipole antenna is located at Q. A typical field point is P.

where $k = 2\pi/\lambda$. The wavelength of the radiation is λ. The inhomogeneous equation for Π is

$$(\nabla^2 + k^2)\Pi = -\frac{I\,dz_0}{i\omega\epsilon}\,\delta(\mathbf{r} - \mathbf{r}_0) \tag{15}$$

where $\delta(\vec{r} - \vec{r}_0)$ is the three-dimensional Dirac function, and $\vec{r}$ is the vector from the origin to point P, and $\vec{r}_0$, to point Q.

At the metal walls, which have very large electrical conductivity, the electric field must be zero. To satisfy the boundary condition at the walls, Π is zero at $\phi = 0$ and $\phi = \psi$. Symmetry relative to the plane containing the dipole also requires Π to be zero when $\phi = \phi_0$.

A Fourier series can be used for Π in the ϕ direction which will satisfy the conditions at $\phi = 0$, ϕ_0, and ψ. The series is

$$\Pi = \sum_{m=0}^{\infty} \epsilon_m \Pi_m(\rho, z) \sin\frac{m\pi}{\psi}\phi \sin\frac{m\pi}{\psi}\phi_0 \tag{16}$$

where $\epsilon_0 = 1$ and $\epsilon_m = 2$ when m is not zero. The function Π_m is given by

$$\Pi_m(\rho, z) = \frac{1}{\psi}\int_0^{\phi} \Pi \sin\frac{m\pi}{\psi}\phi \sin\frac{m\pi}{\psi}\phi_0\, d\phi \tag{17}$$

For the problem at hand, z extends to $+\infty$ and to $-\infty$; that gives a big superstructure! A Fourier integral is used for the z direction

$$\Pi_m(\rho, z) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} \bar{\Pi}_m(\rho) \exp[-ih(z - z_0)]\, dh \tag{18}$$

with the inverse pair

$$\bar{\Pi}_m(\rho) = \int_{-\infty}^{+\infty} \Pi_m(\rho, z) \exp[ih(z - z_0)]\, dz \tag{19}$$

Continuing, Wait [34] shows the solution to be

$$\Pi = -\left(\frac{Idz_0}{4\pi i\epsilon\omega}\right)\frac{i}{2}\frac{\pi}{\psi}\sum_{m=1}^{\infty} 2\sin\nu\phi \sin\nu\phi_0$$

$$\times\int_{-\infty}^{+\infty} H_\nu^{(2)}(v\rho) J_\nu(v\rho_0) \exp[-ih(z - z_0)]\, dh \tag{20}$$

where $\nu = m\pi/\psi$ and $v = (k^2 - h^2)^{1/2}$. $H_\nu^{(2)}$ is a Hankel function of order ν. J_ν is Bessels function of order ν.

For the case where $\psi = \pi/N$, the solution reduces to

$$\Pi = \frac{I\,dz_0}{4\pi i\epsilon\omega}\sum_{n=0}^{2(N-1)}\left[\frac{\exp(-ikR_n)}{R_n} - \frac{\exp(-ik\bar{R}_n)}{\bar{R}_n}\right] \tag{21}$$

where

$$R_n = [(\rho_n)^2 + (z - z_0)^2]^{1/2}$$

and

$$\bar{R}_n = [(\bar{\rho}_n) + (z - z_0)^2]^{1/2}$$

The definitions of $\hat{\rho}_n$ and $\bar{\rho}_n$ are

$$\rho_n = \left\{\rho_0^2 + \rho^2 - 2\rho_0\rho\cos\left[\phi - \left(\frac{n\pi}{N} + \phi_0\right)\right]\right\}^{1/2}$$

and

$$\bar{\rho}_n = \left\{\rho_0^2 + \rho^2 - 2\rho_0\rho\cos\left[\phi - \left(\frac{n\pi}{N} - \phi_0\right)\right]\right\}^{1/2}$$

Equation (21) is a solution by images.

From this example, one recognizes the essential parts of an analytical approach. The wave equation, which is equation (15) is solved subject to boundary conditions imposed by metal walls. The resulting electromagnetic field is modified significantly by the presence of the metal walls.

The Hertz vector for a single isolated dipole antenna in free space is

$$\Pi = \frac{I\,dz_0}{4\pi i\epsilon\omega}\,\frac{\exp(-ikR)}{R} \tag{22}$$

One can compare equations (21) and (22) to see the modification due to the metal walls.

Obviously the solution of equation (20) or equation (21) is of little practical use since ship superstructures are not two metal plates of infinite

extent. Analytical approaches are of limited value for complex geometrical shapes; numerical solutions to the wave equation using computers is the practical method for obtaining antenna patterns, coupling between antennas, feedpoint impedances, etc. Rockway and DuBrul [22] discuss the numerical approach using the method of moments.

APPENDIX B. LINEAR ALGEBRAIC FORMULATION OF INFLUENCE OF ARRANGEMENTS ON SUBSYSTEMS

One formulation for influence of arrangements on subsystems is linear algebra. The concept, which has considerable appeal, is to use an equation of the form

$$\underset{\text{PERFORMANCE VECTOR}}{\begin{Bmatrix} P_1 \\ P_2 \\ P_3 \\ \cdot \\ \cdot \\ \cdot \\ P_n \end{Bmatrix}} = \underset{\text{INFLUENCE MATRIX}}{\begin{vmatrix} I_{11} & I_{12} & I_{13} & \cdots & I_{1m} \\ I_{21} & I_{22} & \cdots & & \\ I_{31} & \cdots & & & \\ \cdot & & & & \\ \cdot & & & & \\ \cdot & & & & \\ I_{n1} & & & & I_{nm} \end{vmatrix}} \underset{\text{ARRANGEMENTS VECTOR}}{\begin{Bmatrix} A_1 \\ A_2 \\ A_3 \\ \cdot \\ \cdot \\ \cdot \\ A_m \end{Bmatrix}}. \tag{23}$$

The arrangements vector consists solely of a geometric description of a subsystem. Possible geometrical variables include the following:

shape of item . . . . P_3, P_4

location of CG. . . . . P_2

volume. . . . .

surface area. . . . .

characteristic dimension. . . P_1

The symbols P_1 . . P_4 are components of the performance vector and will be discussed shortly.

To determine the applicability of equation (23) as a tool to quantify arrangements, consider the interactions involved in radar. As a model to test equation (23), consider two conical masts located on a barge. Each mast has an antenna at its tip as shown in Figure 3.

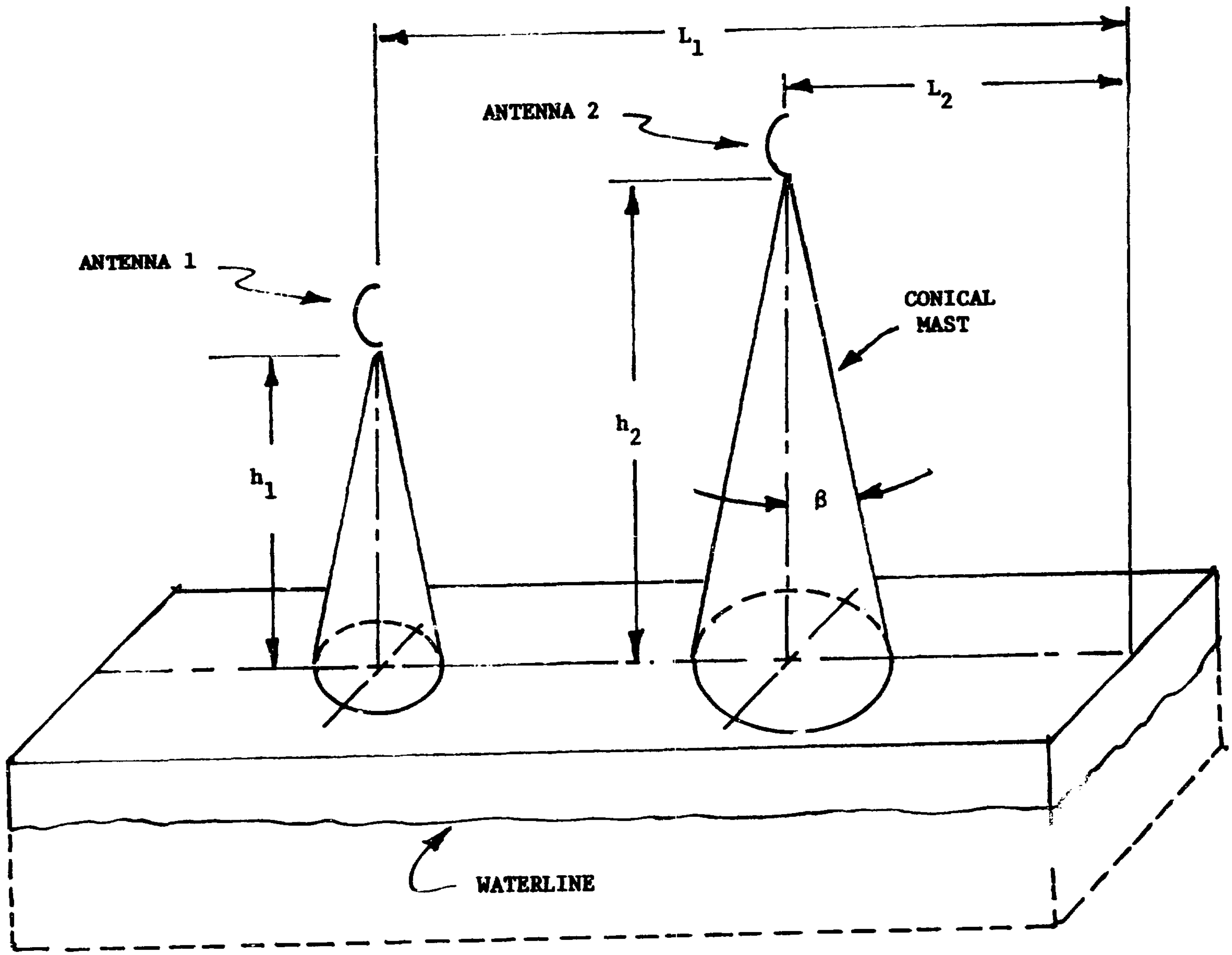

Figure 3. Blockage of radar antennas.

The performance parameters selected are as follows:

P_1 = range to radar horizon

P_2 = weight of antenna stabilization mechanism

P_3 = angles blocked by other subsystems

P_4 = electromagnetic wave distortion caused by adjacent structure; antenna pattern degradation

Each of the performance parameters will now be discussed.

The range to the radar horizon is given by

$$P_1 = R = 1.23[\sqrt{H} + \sqrt{h}] \tag{24}$$

where

R = range to horizon, nm, in a 4/3 atmosphere

H = antenna height above waterline, feet

h = target height above water, feet

Application of rules for evaluation of equation (1) gives

$$P_1 = I_{11}A_1 + I_{12}A_2 + I_{13}A_3 + \dots \tag{25}$$

Comparison of equations (24) and (25) suggests the definitions

$$A_1 = H$$

$$I_{11} = ?$$

$$I_{21} = I_{31} = 0$$

Due to the square root of H, the linear formulation is not applicable.

The weight of the antenna stabilization mechanism depends on roll rates as well as antenna weight itself. The interaction between roll rate and antenna characteristics follows from a series of equations. The shift in the center of gravity, ΔKG, due to the antenna is given by

$$\Delta KG = \frac{m_a(x_a - x_s) + m_m(x_m - x_s)}{m_a + m_s + m_m} \tag{26}$$

where

m_a = mass of antenna

m_m = mass of mast

m_s = mass of ship less antenna and mast

x_a = distance from keel to CG of antenna

x_s = distance from keel CG of ship

x_m = distance from keel to CG of mast

Addition of antenna weight and mast weight changes ship draft, D. The distance from keel to metacenter is in general a function of draft. Hence,

$$KM = f(D) \tag{27}$$

where D is ship draft.

The roll rate follows from the differential equation for roll

$$I\ddot{\theta} + k^2\theta = 0 \tag{28}$$

where I is the moment of inertia of the complete ship about the axis of roll. The quantity $k^2\theta$ is equal to

$$k^2\theta = \Delta(KM - KG)\theta \tag{29}$$

For small angles $\sin\theta \cong \theta$; this assumption has been used in equation (29). The period of roll, τ, is related to k by

$$\tau = 2\pi I^{1/2}/k = 2\pi\left[\frac{I}{\Delta(KM - KG)}\right]^{1/2} \tag{30}$$

In the preceding equations, Δ is the displacement. Addition of the antenna and mast changes Δ, I, KM, and KG. The roll rate is related to τ. The antenna stabilization need not act faster than that required by roll rate. The variables are interacting through equations (26) to (30). P_2 is not formulated here.

Consider now the angles blocked by other subsystems. Reference to Figure 3 shows that antenna 1 is blocked by antenna 2. The blockage needs to be expressed differently for 2D and 3D radars. For 2D radar, only the angle is significant; for 3D radars, the solid angle, steradian, which is blocked is the significant quantity. Assume radar 1 is a 2D radar.

By straightforward geometrical considerations, one can show

$$\alpha = 2 \arcsin \frac{(h_2 - h_1) \tan\beta}{L_2 - L_1} \tag{31}$$

where h_1, h_2, L_1, L_2 and β are defined by Figure 3. The angle α is the angle of radar 1 blocked by conical mast 2. The performance parameter is

$$P_3 = \frac{360 - \alpha}{360} \tag{32}$$

From equation (23)

$$P_3 = I_{31}A_1 + I_{32}A_2 + I_{33}A_3 + I_{34}A_4 + \ldots . \tag{33}$$

Equation (33) suggests $A_4 = h_1$, $A_5 = h_2$, $A_6 = L_1$, $A_7 = L_2$, etc. Further, $I_{31} = I_{32} = I_{33} = 0$. However, comparing equations (31) to (33) indicates, once again, a linear formulation is not possible.

Although equation (23) has an appeal, the problem at hand is not linear.

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